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(54) Single-wafer tunneling sensor and low-cost IC manufacturing method

(57) A tunneling tip sensor (40) and a method of photolithographically fabricating a unitary structure sensor (40) on a semiconductor substrate (42) are disclosed. A cantilever electrode (44) is formed on the substrate (42) with one end suspended above the substrate (42) at a distance from a tunneling electrode (50) so that a tunneling current (55) flows through the cantilever (44) and tunneling (50) electrodes in response to an applied bias voltage. The cantilever (44) and tunneling (50) electrodes form a circuit that produces an output signal (76). A force (56) applied to the sensor (40) urges the cantilever electrode (44) to deflect relative to the tunneling electrode (50) to modulate the output signal (76). The sensor (40) has a unitary structure and the cantilever electrode (44) extends from the substrate (42).

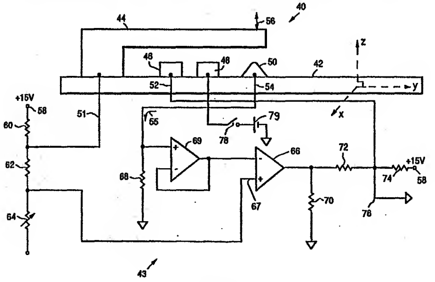

FIG. 2.

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention generally relates to the field of electro-mechanical sensors for measuring an applied force, and more specifically to a tunneling-tip sensor and a photolithography method for fabricating the sensor.

Description of the Related Art

One method for sensing physical quantities such as linear or rotational acceleration, or acoustic or hydrophonic pressure is to provide a flexible member that flexes in response to an applied force and measures the amount of flex electrically. Conventional micro-mechanical techniques for achieving the transduction include capacitive coupling, piezoresistive sensing and piezoelectric sensing. However, none of these techniques are inherently as sensitive as tunneling tip transduction.

In tunneling tip sensors, a bias voltage is applied across a flexible counter electrode and a tunneling tip with a sufficiently small gap between the two components to induce a tunneling current to flow. The tunneling current I_T is given by: $I_T \propto V_B \exp(-\alpha h\sqrt{\phi})$, where V_B is the bias voltage, α is a constant, h is the electrode-to-tip separation and ϕ is the work function. As the applied force changes, the separation between the electrode and the tip changes and modulates the tunneling current, which varies by approximately a factor of three for each angstrom (Å)of electtrode deflection. Thus, tunneling tip detectors can provide a much greater sensitivity and a larger bandwidth than previous method of detections and still provide easily measurable signals.

For the specific application of the sensor as an accelerometer, the deflection distance $x = ma/k$, where m is the electrode's mass, k is the electrode's spring constant and a is the acceleration. The effective bandwidth of the accelerometer is determined by its resonant frequency

$$w=\sqrt{\frac{k}{m}}.$$

Since tunneling tip techniques are more sensitive to deflection, the accelerometer's mass can be relatively small, and thus its bandwidth can be larger than the capacitive coupling and piezoresistive devices.

A tunnel tip sensor and its fabrication method are disclosed in Kenney et al., "Micromachined silicon tunnel sensor for motion detection," Applied Physics Letters Vol. 58, No. 1, January 7, 1991, pages 100-102. A flexible folded cantilever spring and a tunneling tip are formed on a first silicon wafer by etching completely through the wafer to form a proof mask pattern. The pattern defines an inner rectangular area that is suspended by first and second folded flexible members that extend from the outer portion of the wafer to the inner rectangle. The cantilever spring and tunneling tip are formed by thermally evaporating gold through respective shadow masks onto the patterned wafer to define respective contacts on the wafer's outer portion that extend therefrom along the respective folded members to a rectangular mass and a tip on the inner rectangular portion of the wafer. The cantilever spring and tunneling tip are physically connected by the proof mask which allows them to deflect in unison in response to an applied force but are electrically isolated from each other. A second wafer is etched to define a hole approximately the size of the cantilever spring's rectangular mass and a tunneling counter electrode. A third wafer is etched to define a deflection counter electrode approximately the size of the cantilever spring's rectangular mass. The 200 μm thick wafers are then pinned or bonded together by placing the first wafer with the cantilever spring and tip face up on the bottom, and placing the second wafer with the tunneling counter electrode suspended above the tip at a separation of approximately 50 μm and the hole above said cantilever spring's mass. The third wafer is placed on top of the second with the deflection counter electrode disposed above the hole such that it is suspended above the cantilever spring. The three wafers are mechanically attached with alignment pins or epoxy and electrically connected to a separate analog feedback circuit.

A control voltage is applied between the deflection counter electrode and the cantilever spring to provide an attractive force that brings the tip close enough to the tunneling counter electrode for a bias voltage applied between the tunneling counter electrode and the tip to induce a tunneling current of approximately 1.3 nA. The cantilever spring and tip deflect in response to an applied force to modulate the tunneling current. The cantilever spring provides the mass required to produce a measurable deflection and the desired sensitivity for the accelerometer. The analog feedback circuit compares the measured tunneling current to a setpoint, and modulates the control voltage to adjust the separation between the tunneling counter electrode and the tip to maintain a constant current. The modulated control voltage provides an output proportional to the applied force.

Although this tunneling tip sensor provides a more sensitive and compact sensor than the other conventional sensors, its fabrication method and structure have several deficiencies. Fabricating three separate 200 μm wafers and bonding them together produces sensors that are approximately 4 cm^2 in area, with manufacturing yields of approximately 5%. These relatively large size and low yield sensors are very expensive to manufacture. The tip-to-tunneling electrode separation is nominally 50 μm and requires a control voltage of approximately 200 volts to bring the tip close enough to the tunneling electrode to induce the tunneling current. The high voltage levels are not compatible with other TTL or CMOS circuitry and variations in the separation cause large variations in the required control voltage. The cantilever spring has a mass of 30 mg, which restricts the resonant frequency to approximately 200 Hz and a band-

width that is comparable to those of other conventional techniques. The accelerometer fails to achieve a larger bandwidth because of its relatively large mass. The design of the cantilever spring makes the sensor sensitive to off-axis (x or y-axis) forces and large temperature coefficients and drift. Furthermore, when the feedback circuit is turned off, a large shock can deflect the spring, causing the tip to impact the tunneling counter electrode and be damaged due to the relatively large spring mass.

SUMMARY OF THE INVENTION

The present invention seeks to provide a tunneling tip sensor and a method of fabricating the sensor that results in a higher manufacturing yield, smaller size, higher bandwidth, finer tip-to-cantilever control, lower control voltages, lower off-axis sensitivity, lower temperature sensitivity, greater shock resistance and lower cost.

These goals are achieved with a tunneling tip sensor that has a unitary structure and is formed on a semiconductor substrate. A cantilever electrode extends from the substrate with one end suspended above a tunneling electrode on the substrate so that a tunneling current flows between the cantilever and tunneling electrodes in response to an applied bias voltage. The cantilever and tunneling electrodes together define an electrical circuit that is modulated by the cantilever electrodes deflection in response to an applied force. The modulation is sensed either by holding the bias voltage constant and sensing changes in the current, or in the preferred embodiment, by adjusting a control voltage between the cantilever electrode and a control electrode to maintain the current constant and using changes in the control voltage as an indication of the circuit modulation.

The tunneling tip sensor is fabricated by providing the semiconductor substrate with a layer of conductive material, and photolithographically patterning the conductive material to form a cantilever pad and a tunneling electrode. The cantilever pad is photolithographically extended to form a cantilever arm that is suspended over the substrate such that the arm deflects relative to the tunneling electrode in response to an applied force.

In an alternative embodiment, a lateral control electrode is fabricated to produce a lateral motion of the cantilever arm such that the sensor detects a rotation. In another embodiment, x, y and z-axis sensors are fabricated on a substrate to provide a planar three-axis sensor. In a further embodiment, a 3-D inertial cube sensor includes z-axis and rotational sensors formed on three mutually orthogonal faces to provide x-y-z axis accelerometers and gyros.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1a-1j are sectional views illustrating the photolithography method used to fabricate a z-axis sensor;

FIG. 2 is a sectional view of a completed z-axis sensor including a schematic diagram of an analog feedback circuit;

FIG. 3 is a plan view of the z-axis sensor;

FIG. 4 is a perspective view showing a rotational sensor implementation of the invention;

FIG. 5 is a perspective view showing the preferred rotational sensor;

FIG. 6 is a perspective view of a lateral sensor implementation of the invention;

FIGs. 7a-7e are sectional views illustrating the photolithography method for fabricating the lateral sensor shown in FIG. 6;

FIG. 8 is a perspective view of a planar three-axis sensor; and

FIG. 9 is a perspective view of a 3-D inertial cube sensor.

DETAILED DESCRIPTION OF THE INVENTION

FIGs. 1a through 1j show a preferred method for fabricating a z-axis tunneling tip sensor that can be used for measuring forces applied to the sensor by linear or rotational accelerations, or by acoustic or hydrophonic pressures. The preferred method uses photolithography to fabricate the entire sensor as a unitary structure on a semiconductor wafer. As shown in FIG. 1a, the photolithography method starts by thermally evaporating a metal layer 10, preferably gold and approximately 1.2 μm thick, onto a dielectric layer 12 such as SiO_2 that is disposed on a semiconductor substrate 14, preferably silicon. In the next step a negative resist 16, approximately 0.2-0.5 μm high, is patterned over the metal layer 10 (FIG. 1b). The metal layer 10 is then etched by an ion milling process of Ar^+ at 500 eV to a thickness of approximately 0.7 μm to define a tip 18 having a height of approximately 0.5 μm (FIG. 1c). The negative resist 16 is gradually eroded by the ion milling process so that the tip is graded from a relatively wide base to an upper end. In subsequent steps the negative resist 16 is removed and a positive resist 20 is patterned over the metal layer 10 and tip 18 (FIG. 1d). The metal layer 10 is etched with a similar ion milling process through to the SiO_2 layer 12 to define a cantilever pad 22, a control electrode 24, a test electrode 26 and a tunneling electrode 28 that includes the tip 18 (FIG. 1e).

In the next step the resist 20 is removed and a sacrificial layer 30, preferably a photoresist, is patterned over substrate 14 to expose the cantilever pad 22 (FIG. 1f). The sacrificial layer 30 extends upwardly approximately 1 μm from the top of the cantilever pad 22. (It can be planarized by using photolithography to remove the sacrificial layer over the electrodes and then spinning additional resist on top of the wafer to the required thickness.)

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Alternatively the sacrificial layer could be a spin-on glass material or an oxide such as silicon dioxide. A thin layer of metal 32, approximately 200 Å thick and preferably gold, is evaporated over the wafer to form a solid contact with the cantilever pad 22 (FIG. 1g). In the next step a resist 34 is patterned over the metal layer 32 to define a void that extends from the end of the tunneling electrode 28 to the far end of the cantilever pad 22 (FIG. 1h). The thin metal layer 32 forms a base for plating on a metal electrode 36 by electrolysis in the next step (FIG. 1i). The electrode 36 is preferably gold and approximately 400 Å to 10 µm thick, 2-400 µm wide and 10-1000 µm long. This method can produce a low stress electrode 36 that will not bend under its own stress when suspended. In the last steps (FIG. 1j) the resist 34 is removed, the exposed portions of layer 32 are removed by ion milling, and sacrificial layer 30 is removed. Various methods of sacrificial layer removal can be utilized to minimize stiction problems. These include but are not limited to various high vapor pressure liquid rinses, O_2 plasma ashing or critical point drying. This leaves a cantilever arm 38 attached to the cantilever pad 22 and suspended above substrate 14. The control electrode 24, test electrode 26 and tip 18 are exposed, with an arm-to-tip distance of approximately 0.5 µm. Making the width of the cantilever arm 38 much greater than its thickness reduces the sensor's sensitivity to off-axis forces.

In an alternative embodiment, the tip 18 is formed on the underside of cantilever arm 38 instead of on the tunneling electrode 28. In this case the fabrication steps of FIGs. 1b and 1c are omitted, and the tip is formed by etching a tapered depression with a shape complementary to the desired tip shape in the sacrificial layer 30 above the tunneling electrode before the gold layers 32, 36 are added. The result is a cantilever electrode with a tunneling tip suspended above the tunneling electrode.

FIG. 2 shows a sectional view of a z-axis tunneling tip sensor 40 that has been fabricated as described in connection with FIGs. 1a-1j on a semiconductor wafer 42 that lies in the plane defined by the x and y axes, together with an analog feedback circuit 43 that controls its operation. FIG. 3 is a plan view of the z-axis sensor 40 that lies in the xy-plane and extends therefrom. One end of a cantilever electrode 44 is affixed to the wafer, while its other end is suspended approximately 1-2 µm above the wafer's surface over a control electrode 46, a test electrode 48 and a tunneling tip electrode 50. Device encapsulation can be accomplished with several packaging designs if needed for environmental control or vacuum operation.

Circuit 43 applies a control voltage via leads 51 and 52 across the cantilever electrode 44 and the control electrode 46 to create an attractive electric field which pulls the cantilever down to a reference position close to the tunneling tip, e.g., 1-2 nm away from the tip. The circuit also applies a bias voltage via leads 51 and 54 across the cantilever electrode and tip sufficient to initiate a flow of tunneling current 55 through them. The circuit is designed to respond to a deflection of cantilever arm 44 by modulating the control voltage while holding the tunneling current constant, so that the value of the control voltage at any given time indicates the degree of cantilever arm flexure. Alternatively, the control voltage could be held constant and tunneling current modulated, or a combination of both approaches could be used, but modulating the control voltages makes the device less susceptible to damage and effectively linearizes the output signal.

In circuit 43 a supply voltage is applied via a reference terminal 58 across a series connection of resistors 60, 62 and a variable resistor 64, preferably 1 MΩ, 10 kΩ and nominally 2 kΩ to ground reference potential. The cantilever electrode 44 is electrically connected to the junction of resistors 60 and 62, and the junction of resistors 62 and 64 is connected to the non-inverting input 67 of an operational amplifier 66 to provide a reference voltage. The tunneling electrode 50 is connected through an input resistor 68 to ground reference potential, and is also connected to the non-inverting input of an operational amplifier 69. The amplifier 69 is connected as a voltage follower, with its output connected to amplifier 66's inverting input. The output of amplifier 66 is connected through a resistor 70, preferably 10 kΩ, to ground potential and through a series connection of resistors 72 and 74, preferably 4 MΩ and 1 MΩ, to the supply potential terminal 58. The junction of resistors 72 and 74 is electrically connected to control electrode 46 via line 52 to provide the control voltage, which is monitored at output node 76 and is generally proportional to the square root of an applied force 56. The value of resistor 64 is selected to equalize the voltages at amplifier 66's differential inputs for a reference value of tunneling current, preferably 1 nA, such that the amplifier's output is zero when the cantilever arm is undeflected from the reference position and the control voltage remains constant.

The applied force 56, which may be due for example to an acceleration or an acoustic or hydrophonic pressure wave, tends to deflect the cantilever arm. This initially alters the tunneling current 55 and produces unbalanced differential inputs for amplifier 66. The amplifier responds by modulating the control voltage on lead 52 to produce an opposing force to the applied force, thus maintaining a constant cantilever-to-tunneling electrode separation and a constant tunneling current 55. If the applied force causes the cantilever to bend upwards, the separation increases and the tunneling current decreases such that the voltage at the non-inverting input of amplifier 66 is more than the voltage at its inverting input. The amplifier's output is positive, and thus increases the control voltage and the attractive force on the cantilever arm to bring it back to the reference position. Conversely, if the force tends to deflect the cantilever arm downwards, the tunneling current increases and the amplifier's output goes negative, thus reducing the attractive force and allowing the cantilever spring to pull itself back to the reference position. Without its feedback circuit, the cantilever arm can deflect excessively and damage the tunneling electrode. Furthermore, in the

absence of a feedback circuit the sensor's output would be linear only over very small deflections.

The sensor is calibrated periodically by closing a switch 78 to apply a known voltage from a DC source 79 to the test electrode 48 to simulate an applied force, and measuring the resulting output (calibration) voltage. In normal operation, the output would be scaled by the calibration response to produce a normalized output that compensates for drifts in the sensor performance caused by temperature changes, component aging and the like.

The photolithographic fabrication method produces a very small device having a cantilever mass of approximately 1 µg, while maintaining the sensor's deflection sensitivity. Consequently, when used as an accelerometer, the sensor's resonant frequency can be much higher than previous art and can have an effective bandwidth as high as 250 kHz. Another benefit of the extremely small mass is an improved shock resistance. When the control voltage is turned off, the cantilever arm can deflect in response to a large acceleration and may slam into and damage the tip. However, because the mass is very small, the tip pressure for a given acceleration will be much smaller than previous art.

FIG. 4 is a perspective view of a rotational sensor 80. The sensor 80 includes a z-axis sensor 81 and a control circuit which are essentially the same as the sensor 40 and circuit 43 of FIG. 2. In addition, a lateral control electrode 82 is disposed adjacent the cantilever electrode 83 of sensor 80 and is modulated with a voltage to induce a lateral vibration at a known maximum velocity $\overline{V_l}$ in the cantilever electrode. Sensor 80 measures a Coriolis force $\overline{F_c}$ given by: $\overline{F_c}=\frac{1}{2}m\overline{W_r}\times\overline{V_l}$ where m is the cantilever electrode's mass, $\overline{W_r}$ is the rotational rate and $\overline{V_l}$ is the cantilever electrode's lateral velocity. The rotational rate can be determined by measuring the Coriolis force, which is directly proportional to the rotation. In this embodiment, linear accelerations can produce additional deflections, causing incorrect estimates of the rotational rate. By placing a second rotation sensor on the wafer parallel to sensor 80 and laterally oscillating their respective cantilever electrodes 180° out of phase with each other, linear accelerations cancel each other.

FIG. 5 is a perspective view of a preferred embodiment of a rotational sensor 84 on a wafer 85 that is insensitive to linear acceleration forces. A double-ended tuning fork 86 is suspended above and parallel to the wafer 85 by a cross-beam 87 which is supported at its ends by posts 88a and 88b and is orthogonal to the tuning fork. The double tuning fork and cross-beam are preferably fabricated at the same step such that they form a unitary structure. Alternatively, the tuning fork can be formed on top of the cross-beam.

One end of the tuning fork 86 forks into a pair of cantilever beams 89 and 90 that are positioned parallel to a rotation axis 91 and have associated lateral control electrodes 92 and 93 respectively. The other end of the tuning fork 86 forks into a pair of cantilever electrodes 94 and 95 that are suspended above respective control electrodes 96 and 97 and respective tunneling electrodes 98 and 99, which are connected to control circuits similar to the one described in FIG. 2 to maintain constant tunneling currents. The forked ends are interconnected by a cantilever member 152 which is attached to the cross-beam.

The voltages applied to respective lateral electrodes 92 and 93 are modulated in synchronism such that their cantilever beams 89, 90 move 180° out of phase with each other in the plane of the wafer 85. As the sensor 84 rotates around its axis 91, equal but opposite z-axis forces $\overline{F_c}$ are applied to the respective cantilever beams to move them perpendicular to the surface of the wafer, producing a torque on the cantilever member 152 proportional to the Coriolis force. The torque tries to deflect the cantilever electrodes 94 and 95 but is opposed by the feedback circuitry. The rotational rate can be determined by taking the difference between the respective outputs. By moving the cantilever beams 89 and 90 180° out of phase with each other, the changes in the positions of cantilevers 94 and 95 due to linear accelerations are subtracted out and do not affect the rotation signal. The double-ended tuning fork configuration improves performance by separating the sensor fork (electrodes 94 and 95) from the drive fork (electrodes 89 and 90), thereby reducing the noise in the rotation signal.

FIG. 6 is a perspective view of a tunneling tip sensor 100 for measuring lateral (x or y axis) forces. The sensor is formed on a semiconductor wafer 102. A cantilever electrode 104 extends from the wafer and includes an L-shaped section 106 with a tunneling tip 108 at its end. A tunneling electrode 110 is disposed adjacent and at the same height as the tunneling tip 108, with a separation of approximately 0.5 µm between the tunneling tip and the electrode. A control electrode 112 is formed adjacent and at the same height as the cantilever electrode. Alternatively, the tunneling tip 108 could be formed on the tunneling electrode instead of on the cantilever electrode. The cantilever arm deflects in the x-y plane perpendicular to the longer portion of the L-shaped section 106 in response to x or y axis forces, and modulates a tunneling current between the tunneling tip and electrode. An analog control circuit (not shown) similar to the one described in FIG. 2 is preferably used to maintain the tunneling current at a constant value. The sensor's sensitivity to z-axis forces is decreased by making its height or thickness several times its width.

FIGs. 7a-7e are sectional views illustrating a preferred photolithographic technique for fabricating the lateral sensor 100 shown in FIG. 6. The cross-section is taken along the central axis of the cantilever electrode 104 and as such does not show the tunneling electrode, control electrode or tunneling tip, although these components are formed in the same photolithographic steps. In the first step a semiconductor wafer is provided with a semiconductor substrate 114, preferably silicon, a dielectric layer 116, preferably SiO_2, and a conductor layer 118, preferably gold (FIG. 7a). In the next step a photoresist is patterned onto the wafer and the conductor layer

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118 is etched to define a cantilever pad 120, and control and tunneling pads adjacent the cantilever pad (not shown)(FIG. 7b). A sacrificial layer 122 is patterned to expose the three pads and a thin metal layer 124 is thermally evaporated over the wafer (FIG. 7c). In the next step another photoresist 126 is patterned to expose portions of metal layer 124 and a conductor layer 128, e.g. 1-4 µm thick, is electroplated onto the exposed portions of metal layer 124 to form the cantilever electrode and extend the tunneling and control pads to form the tunneling and control electrodes at the same height as the cantilever electrode (FIG. 7d). In the last steps resist 126 is dissolved, the exposed portions of layer 124 are removed by ion milling and the sacrificial layer 122 is removed either by wet or dry techniques as described previously (FIG. 7e).

FIG. 8 is a perspective view of a planar x, y and z-axis sensor that incorporates the individual sensor structures and fabrication methods described above. X, y and z axis sensors 130, 132 and 134 are formed in a unitary structure on a semiconductor wafer 136 to produce a planar sensor device that senses forces in three dimensions. The individual sensors are connected to respective analog feedback circuits 137 and operate as described above. Note that the fabrication sequence for the x and y-axis devices can be incorporated into the sequence for the z-axis device without additional processing steps. In addition, x and y-axis rotation sensors can be added to the wafer using the same process sequence.

FIG. 9 is a perspective view of a 3-D inertial cube that incorporates the z-axis and rotation sensors described previously. X, y- and z-axis sensors 138, 140 and 142 and rotation sensors 144, 146 and 148 are fabricated on respective wafers, which are attached to the mutually orthogonal faces of a cube 150 and electrically connected to respective analog feedback circuits 151. The cube senses 3-axis forces and rotations and can have a volume less than 8 mm^3. While a truly cubic structure is shown in FIG. 9, the important feature is that the three groups of sensors lie in mutually orthogonal planes. An equivalent orientation can be achieved with other geometric shapes, such as a block in which at least one face is a rectangle. The term "cubic" is used herein as a convenient shorthand to refer to any shape with three mutually orthogonal planes, not just a true cube. Other combinations of x-y-z axis sensors and rotation sensors can be implemented on each orthogonal face.

The described photolithographic process and resulting sensor structures have several advantages. Because the sensors are formed as unitary structures, the manufacturing yields are much higher than with previous methods, yields of approximately 80-90% can be achieved, with an accompanying reduction in production time and cost. The individual sensors can be less than 1 mm^2, with a cantilever arm mass of approximately 1 µg and bandwidth of 250 kHz. Thus the die size can be small, allowing more devices to be fabricated per wafer, and therefore at lower cost per device. The unbiased tip-to-cantilever distance can be only about 0.5 µm and can be pulled down to only a couple of nanometers with the application of a control voltage less than 20 V, thus allowing relatively low TTL and CMOS compatible supply voltages. The structure of the sensors reduces their sensitivity to off-axis forces, improves shock resistance, increases bandwidth and reduces temperature drift.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternative embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined by the appended claims.

Claims

1. A tunneling tip sensor comprising:

   - a semiconductor substrate (14; 42; 85; 102; 114; 136);
   - a tunneling electrode (28; 50; 98, 99; 110) on said substrate (14; 42; 85; 102; 114; 136); and
   - a cantilever electrode (44; 83; 89, 90, 94, 95; 104) having one end suspended above said substrate (14; 42; 85; 102; 114; 136) at a distance from said tunneling electrode ((28; 50; 98, 99; 110) so that a tunneling current (55) flows between said cantilever (44; 83; 89, 90, 94, 95; 104) and tunneling (28; 50; 98, 99; 110) electrodes in response to a bias voltage applied across said electrodes (28; 50; 98, 99; 110/44; 83; 89, 90, 94, 95; 104), said cantilever (44; 83; 89, 90, 94, 95; 104) and tunnelling (28; 50; 98, 99; 110) electrodes forming a circuit that produces an output signal (76) such that an applied force (56) which urges said cantilever electrode (44; 83; 89, 90, 94, 95; 104) to deflect relative to said tunneling electrode (28; 50; 98, 99; 110) modulates said output signal (76),

   characterized in that said sensor (40; 80; 84; 100) has a unitary structure and that said cantilever electrode (44; 83; 89, 90, 94, 95; 104) extends from said substrate (14; 42; 85; 102; 114; 136).

2. The sensor of claim 1, characterized in that said substrate (14; 42; 85; 102; 114) lies in an xy-plane with said cantilever electrode (44; 83; 94, 95) suspended above said tunneling electrode (28; 50; 98) and deflecting along a z-axis.

3. The sensor of claim 2, characterized in that said tunneling electrode (50) comprises a tunneling tip (18) that is oriented along the z-axis.

4. The sensor of any of claims 1 - 3, characterized by a control electrode (24; 46; 96, 97; 112) on said substrate (14; 42; 85; 102; 114; 136) below said sus-

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pended cantilever electrode (44; 94, 95; 104), said circuit applying a control voltage as said output signals (76) across said cantilever (44; 94, 95; 104) and control (24; 46; 96, 97; 112) electrodes to control the position of the cantilever electrode (44; 94, 95; 104), and modulating said control voltage to offset said applied force (56) and maintain said tunneling current (55) at a substantially constant level.

5. The sensor of any of claims 1 - 4, characterized by a lateral control electrode (82; 92) on said substrate (85) adjacent said cantilever electrode (83; 89, 90) for producing another force that laterally oscillates the cantilever electrode (83; 89, 90) in response to a corresponding oscillating voltage across the control (82; 92) and cantilever (83; 89, 90) electrodes such that when said sensor (80; 84) is rotated about an axis (91) parallel to the cantilever electrode (83; 89, 90), said applied force is proportional to the rotational rate.

6. The sensor of claim 1, characterized in that said substrate (102) lies in an xy-plane and said cantilever electrode (106) is suspended adjacent said tunneling electrode (110) and deflects laterally in the xy-plane.

7. A method for fabricating a tunneling tip sensor (40; 80; 84) for sensing a z-axis force (56) and having a unitary structure, comprising the steps of:

- providing a base member comprising a semiconductor substrate (14; 42; 85) that lies in the xy-plane with a layer of conductive material (10);
- photolithographically patterning the conductive material (10) to form a cantilever pad (22) and a tunneling electrode (28; 50; 98, 99);
- photolithographically extending the cantilever pad (22) to form a cantilever electrode (32, 36, 38; 44; 83; 94, 95) that extends over the tunneling electrode (28; 50; 98, 99), so that a tunneling current (55) flows between the cantilever (32, 36, 38; 44; 83; 94, 95) and tunneling (28; 50; 98, 99) electrodes in response to an applied bias voltage across the two electrodes (32, 36, 38; 44; 83; 94, 95/28; 50; 98, 99), said cantilever (32, 36, 38; 44; 83; 94, 95) and tunneling (28; 50; 98, 99) electrodes forming a circuit that produces an output signal (76) such that an applied force (56) which urges said cantilever electrode (32, 36, 38; 44; 83; 94, 95) to deflect relative to said tunneling electrode (28; 50; 98, 99) modulates said output signal (76).

8. The method of claim 7, characterized in that the semiconductor substrate (14) is provided with a conductive tip (18) on the conductive layer (12) such that the tunneling electrode (28) includes the tip (18).

9. The method of claim 8, characterized in that the step of providing the base member comprises:

- providing the semiconductor substrate (14);
- depositing the layer of conductive material (10) over the substrate (14) with a known thickness;
- patterning a resist (16) over the conductive layer (10) to expose a portion of the layer (10);
- ion milling the exposed portion of the conductive layer (10) to a reduced thickness to form the conductive tip (18) beneath the resist (16); and
- removing the resist (16).

10. The method of claim 9, characterized in that the resist (16) is a negative resist that erodes during ion milling so that the tip (18) is graded from a base at the surface of the conductive layer (10) to a narrower upper end.

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FIG. 1a.

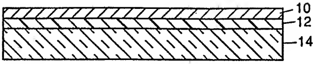


FIG. 1b.

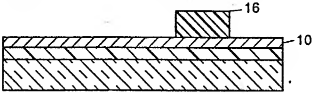


FIG. 1c.

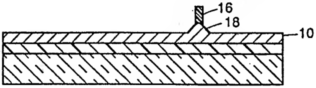


FIG. 1d.

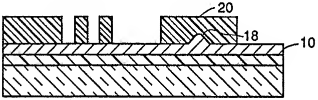


FIG. 1e.

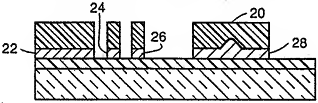


FIG. 1f.

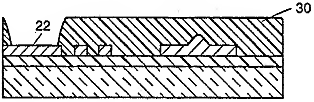


FIG. 1g.

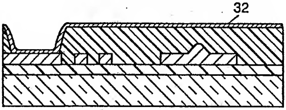
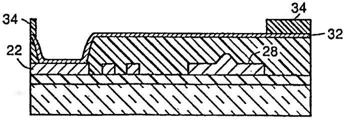


FIG. 1h.



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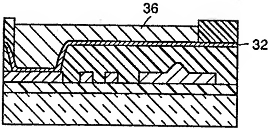

FIG. 1i.

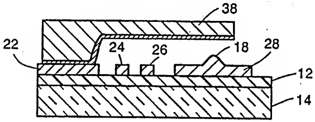

FIG. 1j.

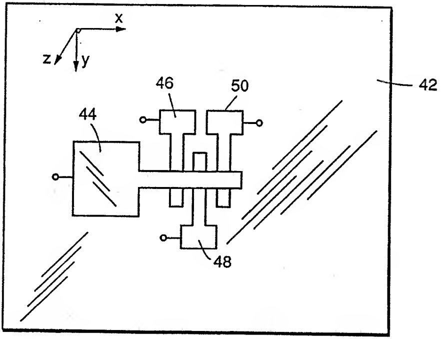

FIG.3.

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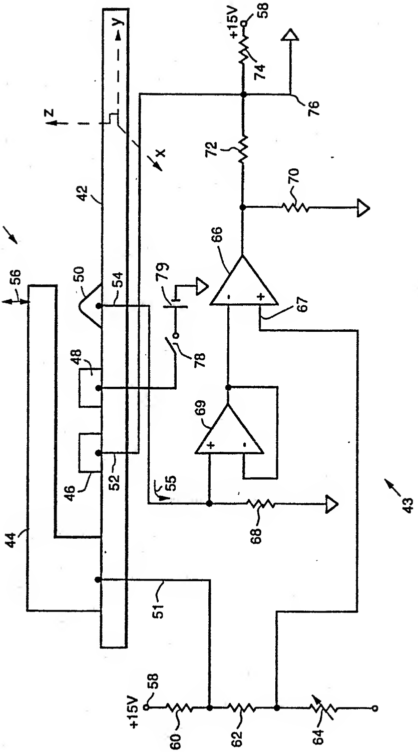

FIG. 2.

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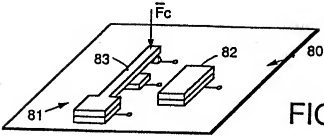

FIG. 4.

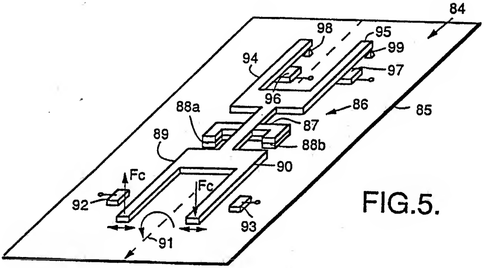

FIG.5.

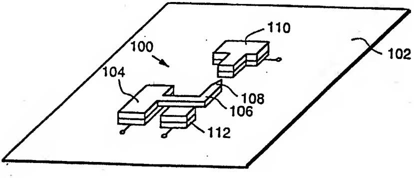

FIG.6.

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FIG. 7a.

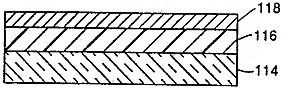


FIG. 7b.

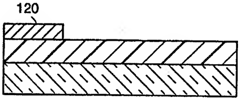


FIG. 7c.

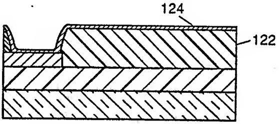


FIG. 7d.

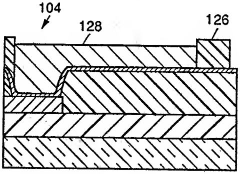
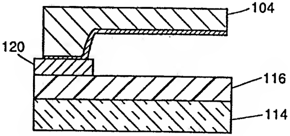


FIG. 7e.



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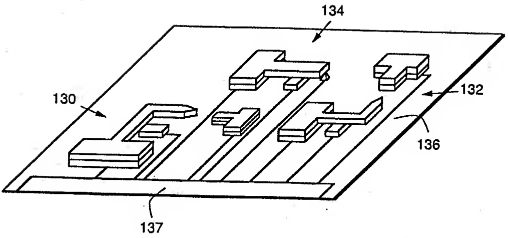

FIG. 8.

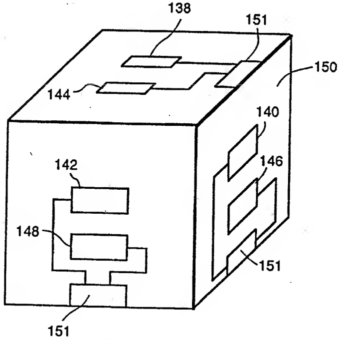

FIG. 9.

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European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 11 2360

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	PROCEEDINGS OF THE WORKSHOP ON MICRO ELECTRO MECHANICAL SYSTEMS, TRAVEMUNDE, FEB. 4 - 7, 1992, no. WORKSHOP 5, 4 February 1992 BENECKE W;PETZOLD H -C, pages 214-219, XP 000344155 DAI KOBAYASHI ET AL 'AN INTEGRATED LATERAL TUNNELING UNIT' * page 214 - page 217 * ---	1-4,6-8	G01P15/08 G01C19/56
Y	JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY A, vol. 11, no. 4, July 1993 - August 1993 NEW YORK, US, pages 797-802, XP 000043707 T.W.KENNY ET AL 'Micromachined tunneling displacement transducers for physical sensors' * page 798; figure 1 * * figure 2 * ---	1-4,6-8	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
A	DE-A-40 32 559 (BOSCH GMBH ROBERT) 16 April 1992 * column 2, line 54 - column 3, line 19 * * abstract * ---	5	G01P G01C
A	PATENT ABSTRACTS OF JAPAN vol. 009 no. 023 (E-293) ,30 January 1985 & JP-A-59 171141 (NIPPON DENKI KK) 27 September 1984, * abstract * ---	9	
A	PATENT ABSTRACTS OF JAPAN vol. 015 no. 288 (E-1092) ,22 July 1991 & JP-A-03 101127 (FUJITSU LTD) 25 April 1991, * abstract * --- -/--	10	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	20 December 1995	Nessmann, C

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

PHI 300027

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 11 2360

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
P,X	EP-A-0 619 494 (SIEMENS AG) 12 October 1994 * column 1, line 49 - column 3, line 45 * ---	1-4,7,8	
A	NTIS TECH NOTES, 1 April 1990 page 346 XP 000128011 'TUNNEL-EFFECT DISPLACEMENT SENSOR' * the whole document * -----	1-4	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)

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D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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PHI 300028

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 701 135 B1

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17.11.1999 Bulletin 1999/46

(51) Int Cl.[6]: **G01P 15/08**, G01C 19/56

(21) Application number: 95112360.3

(22) Date of filing: 05.08.1995

(54) **Single-wafer tunneling sensor and low-cost IC manufacturing method**

Tunneleffektsensor aus Einzelhalbleiterscheibe und kostengünstige IC-Herstellungsmethode

Détecteur à effet de tunnel en plaquette unique et procédé de fabrication économique à circuit intégré

(84) Designated Contracting States:
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(30) Priority: **19.08.1994 US 292897**

(43) Date of publication of application:
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Witte, Weller, Gahlert, Otten & Steil,
Patentanwälte,
Rotebühlstrasse 121
70178 Stuttgart (DE)

(56) References cited:
EP-A- 0 619 494 **DE-A- 4 032 559**

- **PROCEEDINGS OF THE WORKSHOP ON MICRO ELECTRO MECHANICAL SYSTEMS, TRAVEMUNDE, FEB. 4-7, 1992, no. WORKSHOP 5, 4 February 1992 BENECKE W;PETZOLD H -C, pages 214-219, XP 000344155 DAI KOBAYASHI ET AL 'AN INTEGRATED LATERAL TUNNELING UNIT'**
- **JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY A, vol. 11, no. 4, July 1993 - August 1993 NEW YORK, US, pages 797-802, XP 000043707 T.W.KENNY ET AL 'Micromachined tunneling displacement transducers for physical sensors'**
- **PATENT ABSTRACTS OF JAPAN vol. 009 no. 023 (E-293) ,30 January 1985 & JP-A-59 171141 (NIPPON DENKI KK) 27 September 1984,**
- **PATENT ABSTRACTS OF JAPAN vol. 015 no. 288 (E-1092) ,22 July 1991 & JP-A-03 101127 (FUJITSU LTD) 25 April 1991,**
- **NTIS TECH NOTES, 1 April 1990 page 346 XP 000128011 'TUNNEL-EFFECT DISPLACEMENT SENSOR'**
- **KENNY ET AL.: "MICROMACHINED SILICON TUNNEL SENSOR FOR MOTION DETECTION", APPL. PHYS. LETT, , 07-01-1991, vol. 58, no. 1, pages 100 to 102**

EP 0 701 135 B1

Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention generally relates to the field of electro-mechanical sensors for measuring an applied force, and more specifically to a tunneling-tip sensor and a photolithography method for fabricating the sensor.

Description of the Related Art

[0002] One method for sensing physical quantities such as linear or rotational acceleration, or acoustic or hydrophonic pressure is to provide a flexible member that flexes in response to an applied force and measures the amount of flex electrically. Conventional micro-mechanical techniques for achieving the transduction include capacitive coupling, piezoresistive sensing and piezoelectric sensing. However, none of these techniques are inherently as sensitive as tunneling tip transduction.

[0003] In tunneling tip sensors, a bias voltage is applied across a flexible counter electrode and a tunneling tip with a sufficiently small gap between the two components to induce a tunneling current to flow. The tunneling current I_T is given by: $I_T \propto V_B \exp(-\alpha h \sqrt{\phi})$where V_g is the bias voltage, α is a constant, h is the electrode-to-tip separation and ϕ is the work function. As the applied force changes, the separation between the electrode and the tip changes and modulates the tunneling current, which varies by approximately a factor of three for each angstrom (Å) of electrode deflection. Thus, tunneling tip detectors can provide a much greater sensitivity and a larger bandwidth than previous method of detections and still provide easily measurable signals.

[0004] For the specific application of the sensor as an accelerometer, the deflection distance x = ma/k, where m is the electrode's mass, k is the electrode's spring constant and a is the acceleration. The effective bandwidth of the accelerometer is determined by its resonant frequency

$$w = \sqrt{\frac{k}{m}}.$$

Since tunneling tip techniques are more sensitive to deflection, the accelerometer's mass can be relatively small, and thus its bandwidth can be larger than the capacitive coupling and piezoresistive devices.

[0005] A tunnel tip sensor and its fabrication method are disclosed in Kenney et al., "Micromachined silicon tunnel sensor for motion detection," Applied Physics Letters Vol. 58, No. 1, January 7, 1991, pages 100-102. A flexible folded cantilever spring and a tunneling tip are formed on a first silicon wafer by etching completely through the wafer to form a proof mask pattern. The pattern defines an inner rectangular area that is suspended by first and second folded flexible members that extend from the outer portion of the wafer to the inner rectangle. The cantilever spring and tunneling tip are formed by thermally evaporating gold through respective shadow masks onto the patterned wafer to define respective contacts on the wafer's outer portion that extend therefrom along the respective folded members to a rectangular mass and a tip on the inner rectangular portion of the wafer. The cantilever spring and tunneling tip are physically connected by the proof mask which allows them to deflect in unison in response to an applied force but are electrically isolated from each other. A second wafer is etched to define a hole approximately the size of the cantilever spring's rectangular mass and a tunneling counter electrode. A third wafer is etched to define a deflection counter electrode approximately the size of the cantilever spring's rectangular mass. The 200 μm thick wafers are then pinned or bonded together by placing the first wafer with the cantilever spring and tip face up on the bottom, and placing the second wafer with the tunneling counter electrode suspended above the tip at a separation of approximately 50 μm and the hole above said cantilever spring's mass. The third wafer is placed on top of the second with the deflection counter electrode disposed above the hole such that it is suspended above the cantilever spring. The three wafers are mechanically attached with alignment pins or epoxy and electrically connected to a separate analog feedback circuit.

[0006] A control voltage is applied between the deflection counter electrode and the cantilever spring to provide an attractive force that brings the tip close enough to the tunneling counter electrode for a bias voltage applied between the tunneling counter electrode and the tip to induce a tunneling current of approximately 1.3 nA. The cantilever spring and tip deflect in response to an applied force to modulate the tunneling current. The cantilever spring provides the mass required to produce a measurable deflection and the desired sensitivity for the accelerometer. The analog feedback circuit compares the measured tunneling current to a setpoint, and modulates the control voltage to adjust the separation between the tunneling counter electrode and the tip to maintain a constant current. The modulated control voltage provides an output proportional to the applied force.

[0007] Although this tunneling tip sensor provides a more sensitive and compact sensor than the other conventional sensors, its fabrication method and structure have several deficiencies. Fabricating three separate 200 μm wafers and bonding them together produces sensors that are approximately 4 cm^2 in area, with manufacturing yields of approximately 5%. These relatively large size and low yield sensors are very expensive to manufacture. The tip-to-tunnel-ing electrode separation is nominally 50 μm and requires a control voltage of ap-

proximately 200 volts to bring the tip close enough to the tunneling electrode to induce the tunneling current. The high voltage levels are not compatible with other TTL or CMOS circuitry and variations in the separation cause large variations in the required control voltage. The cantilever spring has a mass of 30 mg, which restricts the resonant frequency to approximately 200 Hz and a bandwidth that is comparable to those of other conventional techniques. The accelerometer fails to achieve a larger bandwidth because of its relatively large mass. The design of the cantilever spring makes the sensor sensitive to off-axis (x or y-axis) forces and large temperature coefficients and drift. Furthermore, when the feedback circuit is turned off, a large shock can deflect the spring, causing the tip to impact the tunneling counter electrode and be damaged due to the relatively large spring mass.

[0008] Proceedings of the Workshop on Microelectromechanical Systems, Travemünde, Feb. 4-7, 1992, pp. 214-219, discloses a lateral tunneling unit in which all the elements are integrated on the same wafer, having a cantilever electrode which extends from the substrate.

[0009] Journal of Vacuum Science & Technology, Vol. 11, No. 4, July 1993 - August 1993, pp. 797-802, "Micromachined tunneling displacement transducers for physical sensors", discloses a series of tunneling sensors which take advantage of the extreme position sensitivity of electron tunneling. In these sensors, a tunneling displacements transducer, based on scanning tunneling microscopy principles, is used to detect the signal-induced motion of a sensor element. Through the use of high-resonant frequency mechanical elements for the transducer, sensors may be constructed which offer wide bandwidth, and are robust and easily operated. Silicon micromachining may be used to fabricate the transducer elements, allowing integration of sensor and control electronics.

[0010] EP 0 619 494 A1 discloses an acceleration sensor which is produced on a silicon substrate by etching to leave a cantilever beam of polysilicon with a tip on the substrate projecting toward this beam. Acceleration of the sensor causes the beam to bend, thereby changing the spacing between the tip and the beam, and thereby also changing the tunnel current, which is measured. Electrodes are provided that, given application of a potential thereto, effect an electrostatic compensation of the bending of the beam.

[0011] NTIS Tech Notes, 1 April 1990, page 346, "Tunnel-Effect Displacement Sensor", discloses a tunnel position sensor that measures small displacements or accelerations. The essential elements of this sensor are two electrodes in approximity to each other. One of the electrodes is mounted on a piezoelectric cantilever, which is used to make fine adjustments of the gap between the electrodes. A voltage is supplied between the electrodes. If the electrodes are close enough, then an electrical current flows between them by the quantum-mechanical tunneling effect. The magnitude of this tunneling current is extremely sensitive to the distance between the electrodes, and the variation of the current can therefore be used to measure small displacements of the electrodes relative to each other.

Summary of the Invention

[0012] The present invention seeks to provide a tunneling tip sensor and a method of fabricating a sensor that results in a higher manufacturing yield, smaller size, higher bandwidth, finer tip-to-cantilever control, lower control voltages, lower off-axis sensitivity, lower temperature sensitivity, greater shock resistance and lower cost. These goals are achieved with a tunneling tip sensor that has a unitary structure and is formed on a semiconductor substrate. A cantilever electrode extends from the substrate with one end suspended above a tunneling electrode on the substrate so that a tunneling current flows between the cantilever and tunneling electrodes in response to an applied bias voltage. The cantilever and tunneling electrodes together define an electrical circuit that is modulated by the cantilever electrodes reflection in response to an applied force. The modulation is sensed either by holding the bias voltage constant and sensing the changes in the current, or in the preferred embodiment, by adjusting a control voltage between the cantilever electrode and a control electrode to maintain the current constant and using changes in the control voltage as an indication of the circuit modulation. Further, a lateral control electrode is provided on the substrate adjacent said cantilever electrode for producing another force that laterally oscillates the cantilever electrode in response to a corresponding oscillating voltage across the control and cantilever electrodes such that when said sensor is rotated about an axis parallel to the cantilever electrode, said applied forces proportional to the rotational rate.

[0013] The tunneling tip sensor is fabricated by providing the semiconductor substrate with a layer of conductive material, and photolithographically patterning the conductive material to form a cantilever pad and a tunneling electrode. The cantilever pad is photolithographically extended to form a cantilever arm that is suspended over the substrate such that the arm deflects relative to the tunneling electrode in response to an applied force.

[0014] A lateral control electrode is fabricated to produce a lateral motion of the cantilever arm such that the sensor detects a rotation. In another embodiment, x, y and z-axis sensors are fabricated on a substrate to provide a planar three-axis sensor. In a further embodiment, a 3-D inertial cube sensor includes z-axis and rotational sensors formed on three mutually orthogonal faces to provide x-y-z axis accelerometers and gyros.

[0015] For a better understanding of the invention and to show how the same may be carried into effect reference will now be made, by way of example, to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016]

FIGs. 1a-1j are sectional views illustrating the photolithography method used to fabricate a z-axis sensor;

FIG. 2 is a sectional view of a completed z-axis sensor including a schematic diagram of an analog feedback circuit;

FIG. 3 is a plan view of the z-axis sensor;

FIG. 4 is a perspective view showing a rotational sensor implementation of the invention;

FIG. 5 is a perspective view showing the preferred rotational sensor;

FIG. 6 is a perspective view of a lateral sensor implementation of the invention;

FIGs. 7a-7e are sectional views illustrating the photolithography method for fabricating the lateral sensor shown in FIG. 6;

FIG. 8 is a perspective view of a planar three-axis sensor; and

FIG. 9 is a perspective view of a 3-D inertial cube sensor.

DETAILED DESCRIPTION OF THE INVENTION

[0017] FIGs. 1a through 1j show a preferred method for fabricating a z-axis tunneling tip sensor that can be used for measuring forces applied to the sensor by linear or rotational accelerations, or by acoustic or hydrophonic pressures. The preferred method uses photolithography to fabricate the entire sensor as a unitary structure on a semiconductor wafer. As shown in FIG. 1a, the photolithography method starts by thermally evaporating a metal layer 10, preferably gold and approximately 1.2 µm thick, onto a dielectric layer 12 such as SiO_2 that is disposed on a semiconductor substrate 14, preferably silicon. In the next step a negative resist 16, approximately 0.2-0.5 µm high, is patterned over the metal layer 10 (FIG. 1b). The metal layer 10 is then etched by an ion milling process of Ar^+ at 500 eV to a thickness of approximately 0.7 µm to define a tip 18 having a height of approximately 0.5 µm (FIG. 1c). The negative resist 16 is gradually eroded by the ion milling process so that the tip is graded from a relatively wide base to an upper end. In subsequent steps the negative resist 16 is removed and a positive resist 20 is patterned over the metal layer 10 and tip 18 (FIG. 1d). The metal layer 10 is etched with a similar ion milling process through to the SiO_2 layer 12 to define a cantilever pad 22, a control electrode 24, a test electrode 26 and a tunneling electrode 28 that includes the tip 18 (FIG. 1e).

[0018] In the next step the resist 20 is removed and a sacrificial layer 30, preferably a photoresist, is patterned over substrate 14 to expose the cantilever pad 22 (FIG. 1f). The sacrificial layer 30 extends upwardly approximately 1 µm from the top of the cantilever pad 22. (It can be planarized by using photolithography to remove the sacrificial layer over the electrodes and then spinning additional resist on top of the wafer to the required thickness.) Alternatively the sacrificial layer could be a spin-on glass material or an oxide such as silicon dioxide. A thin layer of metal 32, approximately 200 Å thick and preferably gold, is evaporated over the wafer to form a solid contact with the cantilever pad 22 (FIG. 1g). In the next step a resist 34 is patterned over the metal layer 32 to define a void that extends from the end of the tunneling electrode 28 to the far end of the cantilever pad 22 (FIG. 1h). The thin metal layer 32 forms a base for plating on a metal electrode 36 by electrolysis in the next step (FIG. 1i). The electrode 36 is preferably gold and approximately 400 Å to 10 µm thick, 2-400 µm wide and 10-1000 µm long. This method can produce a low stress electrode 36 that will not bend under its own stress when suspended. In the last steps (FIG. 1j) the resist 34 is removed, the exposed portions of layer 32 are removed by ion milling, and sacrificial layer 30 is removed. Various methods of sacrificial layer removal can be utilized to minimize stiction problems. These include but are not limited to various high vapor pressure liquid rinses, O_2 plasma ashing or critical point drying. This leaves a cantilever arm 38 attached to the cantilever pad 22 and suspended above substrate 14. The control electrode 24, test electrode 26 and tip 18 are exposed, with an arm-to-tip distance of approximately 0.5 µm. Making the width of the cantilever arm 38 much greater than its thickness reduces the sensor's sensitivity to off-axis forces.

[0019] In an alternative embodiment, the tip 18 is formed on the underside of cantilever arm 38 instead of on the tunneling electrode 28. In this case the fabrication steps of FIGs. 1b and 1c are omitted, and the tip is formed by etching a tapered depression with a shape complementary to the desired tip shape in the sacrificial layer 30 above the tunneling electrode before the gold layers 32, 36 are added. The result is a cantilever electrode with a tunneling tip suspended above the tunneling electrode.

[0020] FIG. 2 shows a sectional view of a z-axis tunneling tip sensor 40 that has been fabricated as described in connection with FIGs. 1a-1j on a semiconductor wafer 42 that lies in the plane defined by the x and y axes, together with an analog feedback circuit 43 that controls its operation. FIG. 3 is a plan view of the z-axis sensor 40 that lies in the xy-plane and extends therefrom. One end of a cantilever electrode 44 is affixed to the wafer, while its other end is suspended approximately 1-2 µm above the wafer's surface over a control electrode 46, a test electrode 48 and a tunneling tip electrode 50. Device encapsulation can be accomplished with several packaging designs if needed for environmental control or vacuum operation.

[0021] Circuit 43 applies a control voltage via leads 51 and 52 across the cantilever electrode 44 and the control electrode 46 to create an attractive electric field

which pulls the cantilever down to a reference position close to the tunneling tip, e.g., 1-2 nm away from the tip. The circuit also applies a bias voltage via leads 51 and 54 across the cantilever electrode and tip sufficient to initiate a flow of tunneling current 55 through them. The circuit is designed to respond to a deflection of cantilever arm 44 by modulating the control voltage while holding the tunneling current constant, so that the value of the control voltage at any given time indicates the degree of cantilever arm flexure. Alternatively, the control voltage could be held constant and tunneling current modulated, or a combination of both approaches could be used, but modulating the control voltages makes the device less susceptible to damage and effectively linearizes the output signal.

[0022] In circuit 43 a supply voltage is applied via a reference terminal 58 across a series connection of resistors 60, 62 and a variable resistor 64, preferably 1 MΩ, 10 kΩ and nominally 2 kΩ to ground reference potential. The cantilever electrode 44 is electrically connected to the junction of resistors 60 and 62, and the junction of resistors 62 and 64 is connected to the non-inverting input 67 of an operational amplifier 66 to provide a reference voltage. The tunneling electrode 50 is connected through an input resistor 68 to ground reference potential, and is also connected to the non-inverting input of an operational amplifier 69. The amplifier 69 is connected as a voltage follower, with its output connected to amplifier 66's inverting input. The output of amplifier 66 is connected through a resistor 70, preferably 10 kΩ, to ground potential and through a series connection of resistors 72 and 74, preferably 4 MΩ and 1 MΩ. to the supply potential terminal 58. The junction of resistors 72 and 74 is electrically connected to control electrode 46 via line 52 to provide the control voltage, which is monitored at output node 76 and is generally proportional to the square root of an applied force 56. The value of resistor 64 is selected to equalize the voltages at amplifier 66's differential inputs for a reference value of tunneling current, preferably 1 nA, such that the amplifier's output is zero when the cantilever arm is undeflected from the reference position and the control voltage remains constant.

[0023] The applied force 56, which may be due for example to an acceleration or an acoustic or hydrophonic pressure wave, tends to deflect the cantilever arm. This initially alters the tunneling current 55 and produces unbalanced differential inputs for amplifier 66. The amplifier responds by modulating the control voltage on lead 52 to produce an opposing force to the applied force, thus maintaining a constant cantilever-to-tunneling electrode separation and a constant tunneling current 55. If the applied force causes the cantilever to bend upwards, the separation increases and the tunneling current decreases such that the voltage at the non-inverting input of amplifier 66 is more than the voltage at its inverting input. The amplifier's output is positive, and thus increases the control voltage and the attractive force on the cantilever arm to bring it back to the reference position. Conversely, if the force tends to deflect the cantilever arm downwards, the tunneling current increases and the amplifier's output goes negative, thus reducing the attractive force and allowing the cantilever spring to pull itself back to the reference position. Without its feedback circuit, the cantilever arm can deflect excessively and damage the tunneling electrode. Furthermore, in the absence of a feedback circuit the sensor's output would be linear only over very small deflections.

[0024] The sensor is calibrated periodically by closing a switch 78 to apply a known voltage from a DC source 79 to the test electrode 48 to simulate an applied force, and measuring the resulting output (calibration) voltage. In normal operation, the output would be scaled by the calibration response to produce a normalized output that compensates for drifts in the sensor performance caused by temperature changes, component aging and the like.

[0025] The photolithographic fabrication method produces a very small device having a cantilever mass of approximately 1 µg, while maintaining the sensor's deflection sensitivity. Consequently, when used as an accelerometer, the sensor's resonant frequency can be much higher than previous art and can have an effective bandwidth as high as 250 kHz. Another benefit of the extremely small mass is an improved shock resistance. When the control voltage is turned off, the cantilever arm can deflect in response to a large acceleration and may slam into and damage the tip. However, because the mass is very small, the tip pressure for a given acceleration will be much smaller than previous art.

[0026] FIG. 4 is a perspective view of a rotational sensor 80. The sensor 80 includes a z-axis sensor 81 and a control circuit which are essentially the same as the sensor 40 and circuit 43 of FIG. 2. In addition, a lateral control electrode 82 is disposed adjacent the cantilever electrode 83 of sensor 80 and is modulated with a voltage to induce a lateral vibration at a known maximum velocity $\overline{V}_1$ in the cantilever electrode. Sensor 80 measures a Coriolis force $\overline{F}_c$ given by: $\overline{F}_c = \frac{1}{2} m \overline{W}_r \times \overline{V}_l$; where m is the cantilever electrode's mass, $\overline{W}_r$ is the rotational rate and $\overline{V}_1$ is the cantilever electrode's lateral velocity. The rotational rate can be determined by measuring the Coriolis force, which is directly proportional to the rotation. In this embodiment. linear accelerations can produce additional deflections, causing incorrect estimates of the rotational rate. By placing a second rotation sensor on the wafer parallel to sensor 80 and laterally oscillating their respective cantilever electrodes 180° out of phase with each other, linear accelerations cancel each other.

[0027] FIG. 5 is a perspective view of a preferred embodiment of a rotational sensor 84 on a wafer 85 that is insensitive to linear acceleration forces. A double-ended tuning fork 86 is suspended above and parallel to the wafer 85 by a cross-beam 87 which is supported at its

ends by posts 88a and 88b and is orthogonal to the tuning fork. The double tuning fork and cross-beam are preferably fabricated at the same step such that they form a unitary structure. Alternatively, the tuning fork can be formed on top of the cross-beam.

[0028] One end of the tuning fork 86 forks into a pair of cantilever beams 89 and 90 that are positioned parallel to a rotation axis 91 and have associated lateral control electrodes 92 and 93 respectively. The other end of the tuning fork 86 forks into a pair of cantilever electrodes 94 and 95 that are suspended above respective control electrodes 96 and 97 and respective tunneling electrodes 98 and 99, which are connected to control circuits similar to the one described in FIG. 2 to maintain constant tunneling currents. The forked ends are interconnected by a cantilever member 152 which is attached to the cross-beam.

[0029] The voltages applied to respective lateral electrodes 92 and 93 are modulated in synchronism such that their cantilever beams 89, 90 move 180° out of phase with each other in the plane of the wafer 85. As the sensor 84 rotates around its axis 91, equal but opposite z-axis forces $\overline{F_c}$ are applied to the respective cantilever beams to move them perpendicular to the surface of the wafer, producing a torque on the cantilever member 152 proportional to the Coriolis force. The torque tries to deflect the cantilever electrodes 94 and 95 but is opposed by the feedback circuitry. The rotational rate can be determined by taking the difference between the respective outputs. By moving the cantilever beams 89 and 90 180° out of phase with each other, the changes in the positions of cantilevers 94 and 95 due to linear accelerations are subtracted out and do not affect the rotation signal. The double-ended tuning fork configuration improves performance by separating the sensor fork (electrodes 94 and 95) from the drive fork (electrodes 89 and 90), thereby reducing the noise in the rotation signal.

[0030] FIG. 6 is a perspective view of a tunneling tip sensor 100 for measuring lateral (x or y axis) forces. The sensor is formed on a semiconductor wafer 102. A cantilever electrode 104 extends from the wafer and includes an L-shaped section 106 with a tunneling tip 108 at its end. A tunneling electrode 110 is disposed adjacent and at the same height as the tunneling tip 108, with a separation of approximately 0.5 µm between the tunneling tip and the electrode. A control electrode 112 is formed adjacent and at the same height as the cantilever electrode. Alternatively, the tunneling tip 108 could be formed on the tunneling electrode instead of on the cantilever electrode. The cantilever arm deflects in the x-y plane perpendicular to the longer portion of the L-shaped section 106 in response to x or y axis forces, and modulates a tunneling current between the tunneling tip and electrode. An analog control circuit (not shown) similar to the one described in FIG. 2 is preferably used to maintain the tunneling current at a constant value. The sensor's sensitivity to z-axis forces is decreased by making its height or thickness several times its width.

[0031] FIGs. 7a-7e are sectional views illustrating a preferred photolithographic technique for fabricating the lateral sensor 100 shown in FIG. 6. The cross-section is taken along the central axis of the cantilever electrode 104 and as such does not show the tunneling electrode, control electrode or tunneling tip, although these components are formed in the same photolithographic steps. In the first step a semiconductor wafer is provided with a semiconductor substrate 114, preferably silicon, a dielectric layer 116, preferably SiO_2, and a conductor layer 118, preferably gold (FIG. 7a). In the next step a photoresist is patterned onto the wafer and the conductor layer 118 is etched to define a cantilever pad 120, and control and tunneling pads adjacent the cantilever pad (not shown)(FIG. 7b). A sacrificial layer 122 is patterned to expose the three pads and a thin metal layer 124 is thermally evaporated over the wafer (FIG. 7c). In the next step another photoresist 126 is patterned to expose portions of metal layer 124 and a conductor layer 128, e.g. 1-4 µm thick, is electroplated onto the exposed portions of metal layer 124 to form the cantilever electrode and extend the tunneling and control pads to form the tunneling and control electrodes at the same height as the cantilever electrode (FIG. 7d). In the last steps resist 126 is dissolved, the exposed portions of layer 124 are removed by ion milling and the sacrificial layer 122 is removed either by wet or dry techniques as described previously (FIG. 7e).

[0032] FIG. 8 is a perspective view of a planar x, y and z-axis sensor that incorporates the individual sensor structures and fabrication methods described above. X, y and z axis sensors 130, 132 and 134 are formed in a unitary structure on a semiconductor wafer 136 to produce a planar sensor device that senses forces in three dimensions. The individual sensors are connected to respective analog feedback circuits 137 and operate as described above. Note that the fabrication sequence for the x and y-axis devices can be incorporated into the sequence for the z-axis device without additional processing steps. In addition, x and y-axis rotation sensors can be added to the wafer using the same process sequence.

[0033] FIG. 9 is a perspective view of a 3-D inertial cube that incorporates the z-axis and rotation sensors described previously. X,y- and z-axis sensors 138, 140 and 142 and rotation sensors 144, 146 and 148 are fabricated on respective wafers, which are attached to the mutually orthogonal faces of a cube 150 and electrically connected to respective analog feedback circuits 151. The cube senses 3-axis forces and rotations and can have a volume less than 8 mm^3. While a truly cubic structure is shown in FIG. 9, the important feature is that the three groups of sensors lie in mutually orthogonal planes. An equivalent orientation can be achieved with other geometric shapes, such as a block in which at least one face is a rectangle. The term "cubic" is used

herein as a convenient shorthand to refer to any shape with three mutually orthogonal planes, not just a true cube. Other combinations of x-y-z axis sensors and rotation sensors can be implemented on each orthogonal face.

[0034] The described photolithographic process and resulting sensor structures have several advantages. Because the sensors are formed as unitary structures, the manufacturing yields are much higher than with previous methods, yields of approximately 80-90% can be achieved, with an accompanying reduction in production time and cost. The individual sensors can be less than 1 mm^2, with a cantilever arm mass of approximately 1 μg and bandwidth of 250 kHz. Thus the die size can be small, allowing more devices to be fabricated per wafer, and therefore at lower cost per device. The unbiased tip-to-cantilever distance can be only about 0.5 μm and can be pulled down to only a couple of nanometers with the application of a control voltage less than 20 V, thus allowing relatively low TTL and CMOS compatible supply voltages. The structure of the sensors reduces their sensitivity to off-axis forces, improves shock resistance, increases bandwidth and reduces temperature drift.

[0035] While several illustrative embodiments of the invention have been shown and described, numerous variations and alternative embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the scope of the invention as defined by the appended claims.

Claims

1. A tunneling tip sensor having a unitary structure comprising:

   - a semiconductor substrate (14; 42; 85; 102; 114; 136);
   - a tunneling electrode (28, 50; 98, 99; 110) on said substrate (14; 42; 85; 102; 114; 136); and
   - a cantilever electrode (44; 83; 89, 90, 94, 95; 104) extending from said substrate (14; 42; 85; 102; 114; 136) with one end suspended above said substrate (14; 42; 85; 102; 114; 136) at a distance from said tunneling electrode (28; 50; 98, 99; 110) so that a tunneling current (55) flows between said cantilever (44; 83; 89, 90, 94, 95; 104) and tunneling (28; 50; 98, 99; 110) electrodes in response to a bias voltage applied across said electrodes (28; 50; 98, 99; 110/44; 83, 89, 90, 94, 95, 104), said cantilever (44; 83; 89, 90, 94, 95; 104) and tunneling (28; 50; 98, 99, 110) electrodes forming a circuit that produces an output signal (76) such that an applied force (56) which urges said cantilever electrode (44; 83; 89, 90, 94, 95; 104) to deflect relative to said tunneling electrode (28; 50; 98, 99; 110) modulates said output signal (76),

   characterized by a lateral control electrode (82; 92) on said substrate (85) adjacent said cantilever electrode (83; 89, 90) for producing another force that laterally oscillates the cantilever electrode (83, 89, 90) in response to a corresponding oscillating voltage across the control (82; 92) and cantilever (83; 89, 90) electrodes such that when said sensor (80; 84) is rotated about an axis (91) parallel to the cantilever electrode (83; 89, 90), said applied force is proportional to the rotational rate.

2. The sensor of claim 1, characterized in that said substrate (14; 42; 85; 102; 114) lies in an xy-plane with said cantilever electrode (44; 83; 94, 95) suspended above said tunneling electrode (28; 50; 98) and deflecting along a z-axis.

3. The sensor of claim 2. characterized in that said tunneling electrode (50) comprises a tunneling tip (18) that is oriented along the z-axis.

4. The sensor of any of claims 1 - 3, characterized by a control electrode (24; 46; 96, 97; 112) on said substrate (14; 42; 85; 102; 114; 136) below said suspended cantilever electrode (44; 94, 95; 104), said circuit applying a control voltage as said output signals (76) across said cantilever (44; 94, 95; 104) and control (24; 46; 96, 97; 112) electrodes to control the position of the cantilever electrode (44; 94, 95; 104), and modulating said control voltage to offset said applied force (56) and maintain said tunneling current (55) at a substantially constant level.

5. The sensor of claim 1, characterized in that said substrate (102) lies in an xy-plane and said cantilever electrode (106) is suspended adjacent said tunneling electrode (110) and deflects laterally in the xy-plane.

6. A method of fabricating a tunneling tip sensor (40; 80; 84) for sensing a z-axis force (56) and having a unitary structure, comprising the steps of:

   - providing a base member comprising a semiconductor substrate (14; 42; 85) that lies in an xy-plane with a layer of conductive material (10);
   - depositing the layer of conductive material (10) over the substrate (14) with a known thickness;
   - patterning a resist (16) over the conductive layer (10) to expose a portion of the layer (10);
   - ion milling the exposed portion of the conductive layer (10) to a reduced thickness to form a conductive tip (18) beneath the resist (16);
   - removing the resist (16);
   - photolithographically patterning the conductive

material (10) to form a cantilever pad (22) and a tunneling electrode (28; 50, 98, 99);

- photolithographically extending the cantilever pad (22) to form a cantilever electrode (32, 36, 38; 44; 83; 94, 95) that extends over the tunneling electrode (28; 50; 98, 99), so that a tunneling current (55) flows between the cantilever (32, 36, 38; 44; 83; 94, 95) and tunneling (28; 50, 98, 99) electrodes in response to an applied bias voltage across the two electrodes (32, 36, 38; 44; 83; 94, 95/28; 50; 98, 99), said cantilever (32, 36, 38; 44; 83; 94, 95) and tunneling (28; 50; 98, 99) electrodes forming a circuit that produces an output signal (76) such that an applied force (56) which urges said cantilever electrode (32, 36, 38; 44; 83; 94, 95) to deflect relative to said tunneling electrode (28; 50; 98, 99) modulates said output signal (76); and
- providing the semiconductor substrate (14) provided with a conductive tip (18) on the conductive layer (12) such that the tunneling electrode (28) includes the tip (18), said resist (16) being a negative resist that erodes during ion milling so that the tip (18) is graded from a base at the surface of the conductive layer (10) to a narrower upper end.

Patentansprüche

1. Sensor mit Tunneleffekt-Spitze, der einen einheitlichen Aufbau aufweist, mit

   - einem Halbleitersubstrat (14; 42; 85; 102; 114; 136);
   - einer Tunneleffekt-Elektrode (28; 50; 98, 99; 110) auf dem Substrat (14; 42; 85; 102; 114; 136); und
   - einer freitragenden Elektrode (44; 83; 89, 90, 94, 95; 104), die sich von dem Substrat (14; 42; 85; 102; 114; 136) in einem Abstand von der Tunneleffekt-Elektrode (28; 50; 98, 99; 110) erstreckt, wobei ein Ende über dem Substrat (14; 42, 85, 102; 114, 136) aufgehängt ist, so daß ein Durchtunnelungsstrom (55) zwischen der freitragenden Elektrode (44; 83; 89, 90, 94, 95; 104) und der Tunneleffekt-Elektrode (28; 50; 98, 99, 110) abhängig von einer Vorspannung fließt, die über die Elektroden (28; 50; 98, 99; 110/44; 83; 89, 90, 94, 95; 104) angelegt wird, wobei die freitragende Elektrode (44; 83; 89, 90, 94, 95 104) und die Tunneleffekt-Elektrode (28; 50; 98, 99; 110) eine Schaltung bilden, die ein Ausgangssignal (76) erzeugt, derart, daß eine angelegte Kraft (56), die die freitragende Elektrode (44; 83, 89, 90, 94, 95, 104) zur Auslenkung relativ zu der Tunneleffekt-Elektrode (28; 50; 98, 99; 110) zwingt, das Ausgangssignal (76) moduliert, gekennzeichnet durch eine seitliche Steuerelektrode (82; 92) auf dem Substrat (85) benachbart zu der freitragenden Elektrode (83; 89, 90) zur Erzeugung einer anderen Kraft, die die freitragende Elektrode (83, 89, 90) abhängig von einer entsprechenden Oszillationsspannung an der Steuerelektrode (82; 92) und der freitragenden Elektrode (83; 89, 90) seitlich oszilliert, derart, daß die angelegte Kraft proportional zu der Drehgeschwindigkeit ist, wenn der Sensor (80; 84) um eine Achse (91) parallel zu der freitragenden Elektrode (83; 89, 90) gedreht wird.

2. Sensor nach Anspruch 1, dadurch gekennzeichnet, daß das Substrat (14; 42; 85; 102; 114) in einer xy-Ebene liegt, wobei die freitragende Elektrode (44; 83; 94, 95) über der Tunneleffekt-Elektrode (28; 50; 98) aufgehängt ist und längs einer z-Achse ausgelenkt wird.

3. Sensor nach Anspruch 2, dadurch gekennzeichnet daß die Tunneleffekt-Elektrode (50) eine Tunneleffekt-Spitze (18) umfaßt, die längs der z-Achse ausgerichtet ist.

4. Sensor nach einem der Ansprüche 1 bis 3, gekennzeichnet durch eine Steuerelektrode (24; 46; 96, 97; 112) auf dem Substrat (14, 42, 85, 102, 114. 136) unter der aufgehängten freitragenden Elektrode (44; 94, 95; 104), wobei die Schaltung eine Steuerspannung als Ausgangssignale (76) an die freitragende Elektrode (44; 94, 95; 104) und die Steuerelektrode (24; 46; 96, 97; 112) anlegt, um die Position der freitragenden Elektrode (44; 94, 95: 104) zu steuern, und wobei die Schaltung die Steuerspannung moduliert, um die angelegte Kraft (56) zu verschieben und den Durchtunnelungsstrom (55) auf einem im wesentlichen konstanten Niveau zu halten.

5. Sensor nach Anspruch 1, dadurch gekennzeichnet daß das Substrat (102) in einer xy-Ebene liegt und die freitragende Elektrode (106) benachbart der Tunneleffekt-Elektrode (110) aufgehängt ist und in der xy-Ebene seitlich ausschlägt.

6. Verfahren zur Herstellung eines Sensors mit Tunneleffekt (40; 80; 84) zum Erfassen einer Kraft (56) in z-Richtung, wobei der Sensor einen einheitlichen Aufbau aufweist, mit den Schritten:

   - Vorsehen eines Basiselements, das ein Halbleitersubstrat (14; 42; 85) umfaßt, welches mit einer Schicht aus einem leitfähigen Material (10) in einer xy-Ebene liegt;
   - Auftragen der Schicht eines leitfähigen Materials (10) auf das Substrat (14) mit einer bekann-

ten Dicke;

- Strukturieren eines fotoempfindlichen Lacks (16) auf der leitfähigen Schicht (10), um einen Bereich der Schicht (10) freizulegen;
- Ionenstrahlätzen des freigelegten Bereichs der leitfähigen Schicht (10) auf eine verminderte Dicke, um eine leitfähige Spitze (18) unterhalb des fotoempfindlichen Lacks (16) auszubilden;
- Entfernen des fotoempfindlichen Lacks (16);
- fotolitographisches Strukturieren des leitfähigen Materials (10), um eine freitragende Auflage (22) und eine Tunneleffekt-Elektrode (28; 50; 98, 99) auszubilden;
- fotolitographisches Ausdehnen der freitragenden Auflage (22), um eine freitragende Elektrode (32, 36, 38; 44: 83; 94, 95) auszubilden, die sich über die Tunneleffekt-Elektrode (28; 50; 98, 99) erstreckt, so daß ein Durchtunnelungsstrom (55) zwischen der freitragenden Elektrode (32, 36, 38; 44; 83; 94, 95) und der Tunneleffekt-Elektrode (28; 50; 98, 99) abhängig von einer angelegten Vorspannung an den beiden Elektroden (32, 36, 38; 44; 83; 94, 95/28; 50; 98, 99) fließt, wobei die freitragende Elektrode (32, 36, 38, 44, 83, 94, 95) und die Tunneleffekt-Elektrode (28; 50; 98, 99) eine Schaltung bilden, die ein Ausgangssignal (76) erzeugt in der Art, daß eine angelegte Kraft (56), die die freitragende Elektrode (32, 36, 38, 44, 93, 94, 95) zur Auslenkung relativ zu der Tunneleffekt-Elektrode (28; 50; 98, 99) zwingt, das Ausgangssignal (76) moduliert; und
- Vorsehen des Halbleitersubstrats (14), das mit einer leitfähigen Spitze (18) auf der leitfähigen Schicht (12) versehen ist, derart, daß die Tunneleffekt-Elektrode (28) die Spitze (18) umfaßt, wobei der fotoempfindliche Lack (16) ein negativer fotoempfindlicher Lack ist, der während des Ionenstrahlätzens erodiert, so daß die Spitze (18) von einer Basis an der Oberfläche der leitfähigen Schicht (10) zu einem schmaleren oberen Ende abgestuft wird.

Revendications

1. Capteur à pointe à effet tunnel ayant une structure monolithique, comprenant :

   - un substrat semiconducteur (14 ; 42 ; 85 ; 102 ; 114 ; 136) ;
   - une électrode à effet tunnel (28 ; 50 ; 98, 99 ; 110) sur ledit substrat (14 ; 42 ; 85 ; 102 ; 114 ; 136) ; et
   - une électrode en porte-à-faux (44 ; 83 ; 89, 90, 94, 95 ; 104) s'étendant depuis ledit substrat (14 ; 42 ; 85 ; 102 ; 114 ; 136) et dont une extrémité est suspendue au dessus dudit substrat (14 ; 42 ; 85 ; 102 ; 114 ; 136) à une certaine distance de ladite électrode à effet tunnel (28 ; 50 ; 98, 99 ; 110) afin qu'un courant d'effet tunnel (55) passe entre ledit élément en porte-à-faux (44 ; 83 ; 89, 90, 94, 95 ; 104) et les électrodes à effet tunnel (28 ; 50 ; 98, 99 ; 110) en réponse à une tension de polarisation appliquée entre lesdites électrodes (28 ; 50 ; 98, 99 ; 110/44 ; 83 ; 89, 90, 94, 95 ; 104), lesdites électrodes en porte-à-faux (44 ; 83 ; 89, 90, 94, 95 ; 104) et à effet tunnel (28 ; 50 ; 98, 99 ; 110) formant un circuit qui produit un signal de sortie (76) tel qu'une force appliquée (56) qui sollicite ladite électrode en porte-à-faux (44 ; 83 ; 89 90, 94, 95 ; 104) afin qu'elle soit déviée par rapport à ladite électrode à effet tunnel (28 ; 50 ; 98, 99 ; 110), module ledit signal de sortie (76).

   caractérisé par une électrode de commande latérale (82 ; 92) sur ledit substrat (85) de façon adjacente à ladite électrode en porte-à-faux (83 ; 89, 90) pour produire une autre force qui fait osciller latéralement l'électrode en porte-à-faux (83 ; 89, 90) en réponse à une tension oscillante correspondante entre les électrodes de commande (82 ; 92) et en porte-à-faux (83 ; 89, 90) de telle façon que lorsque ledit capteur (80, 84) est mis en rotation autour d'un axe (91) parallèle à l'électrode en porte-à-faux (83 ; 89, 90), ladite force appliquée soit proportionnelle à la vitesse de rotation

2. Capteur selon la revendication 1, caractérisé en ce que ledit substrat (14 ; 42 ; 85 ; 102 ; 114) se situe dans un plan xy, ladite électrode en porte-à-faux (44 ; 83 ; 94, 95) étant suspendue au-dessus de ladite électrode à effet tunnel (28 ; 50 ; 98) et étant déviée suivant un axe z.

3. Capteur selon la revendication 2, caractérisé en ce que ladite électrode à effet tunnel (50) comprend une pointe à effet tunnel (18) qui est orientée suivant l'axe z.

4. Capteur selon l'une quelconque des revendications 1 - 3, caractérisé par une électrode de commande (24 ; 46 ; 96, 97 ; 112) sur ledit substrat (14 ; 42 ; 85 ; 102 ; 114 ; 136) située en dessous de ladite électrode en porte-à-faux suspendue (44 ; 94, 95 ; 104), ledit circuit appliquant une tension de commande en tant que lesdits signaux de sortie (76) entre lesdites électrodes en porte-à-faux (44 ; 94, 95 ; 104) et de commande (24 ; 46 ; 96, 97 ; 112) pour commander la position de l'électrode en porte-à-faux (44 ; 94, 95 ; 104), et modulant ladite tension de commande pour compenser ladite force appliquée (56) et maintenir ledit courant d'effet tunnel (55) à un niveau sensiblement constant.

5. Capteur selon la revendication 1, caractérisé en ce que ledit substrat (102) se situe dans un plan xy et ladite électrode en porte-à-faux (106) est suspendue à proximité immédiate de ladite électrode à effet tunnel (110) et est déviée latéralement dans le plan xy.

6. Procédé de fabrication d'un capteur à pointe à effet tunnel (40 ; 80 ; 84) pour détecter une force d'axe z (56) et ayant une structure monolithique, comprenant les étapes :

- d'application à un élément de base comprenant un substrat semiconducteur (14 ; 42 ; 85) qui se situe dans un plan xy, d'une couche de matériau conducteur (10) ;
- de dépôt de la couche de matériau conducteur (10) sur le substrat (14) avec une épaisseur connue ;
- de réalisation d'un motif de résist (16) sur la couche conductrice (10) pour exposer une partie de la couche (10) ;
- d'usinage ionique de la partie exposée de la couche conductrice (10) jusqu'à une épaisseur réduite afin de former une pointe conductrice (18) en dessous du résist (16) ;
- d'enlèvement du résist (16) ;
- de réalisation de façon photolithographique d'un motif du matériau conducteur (10) afin de former une plage en porte-à-faux (22) et une électrode à effet tunnel (28 ; 50 ; 98 ; 99) ;
- de prolongement de façon photolithographique de la plage en porte-à-faux (22) afin de former une électrode en porte-à-faux (32, 36, 38 ; 44 ; 83 ; 94, 95) qui se prolonge au-dessus de l'électrode à effet tunnel (28 ; 50 ; 98, 99), afin qu'un courant d'effet tunnel (55) passe entre les électrodes en porte-à-faux (32, 36, 38 ; 44 ; 83 ; 94, 95) et à effet tunnel (28 ; 50 ; 98, 99) en réponse à une tension de polarisation appliquée entre les deux électrodes (32, 36, 38 ; 44 ; 83 ; 94, 95/28 ; 50 ; 98, 99), lesdites électrodes en porte-à-faux (32, 36, 38 ; 44 ; 83 ; 94, 95) et à effet tunnel (28 ; 50 ; 98, 99) formant un circuit qui produit un signal de sortie (76) tel qu'une force appliquée (56) qui sollicite ladite électrode en porte-à-faux (32, 36, 38 ; 44 ; 83 ; 94, 95) pour qu'elle soit déviée par rapport à ladite électrode à effet tunnel (28 ; 50 ; 98, 99) module ledit signal de sortie (76) ; et
- d'utilisation du substrat semiconducteur (14) muni d'une pointe conductrice (18) sur la couche conductrice (12) de façon que l'électrode d'effet tunnel (28) comprenne la pointe (18),

ledit résist (16) étant un résist négatif qui s'érode pendant l'usinage ionique de telle sorte que la pointe (18) présente un gradient d'une base se situant à la surface de la couche conductrice (10) jusqu'à une extrémité supérieure plus étroite.

FIG. 1a.

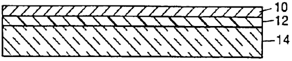


FIG. 1b.

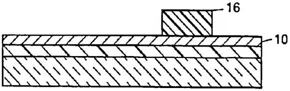


FIG. 1c.

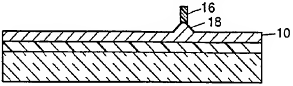


FIG. 1d.

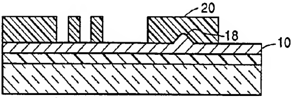


FIG. 1e.

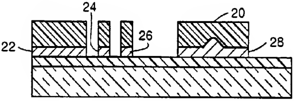


FIG. 1f.

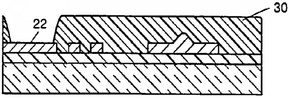


FIG. 1g.

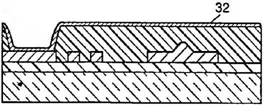
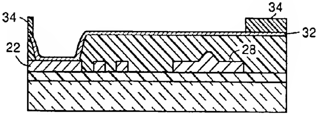


FIG. 1h.



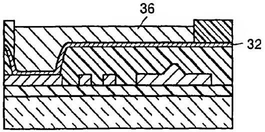


FIG. 1i.

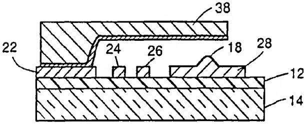


FIG. 1j.

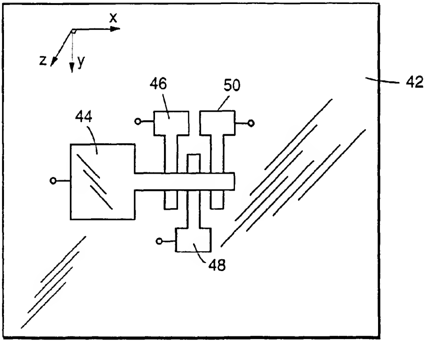


FIG.3.

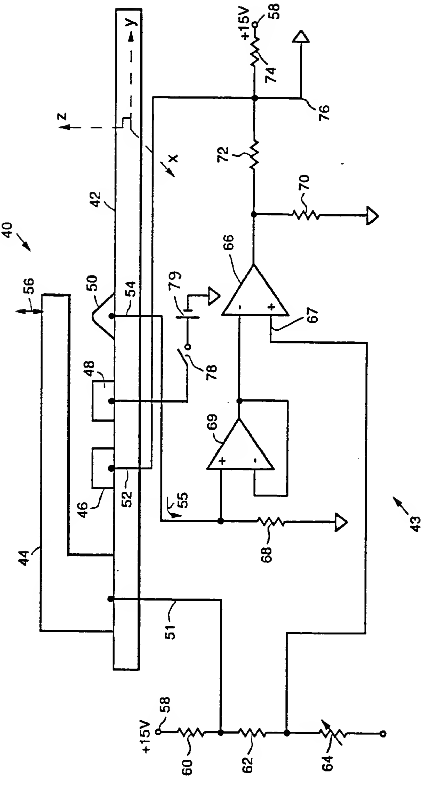

40
42
44
46
48
50
51
52
54
55
56
58
+15V
60
62
64
66
67
68
69
70
72
74
76
78
79
43
x
y
z

FIG. 2.

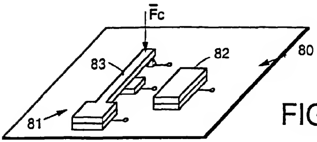


FIG. 4.

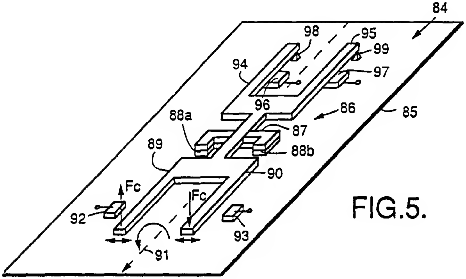


FIG.5.

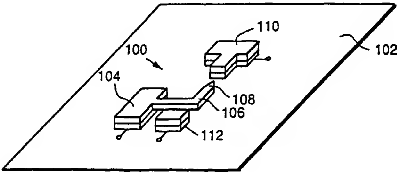


FIG.6.

FIG. 7a.

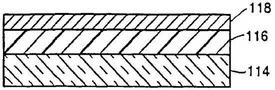


FIG. 7b.

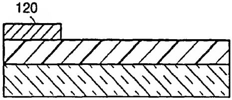


FIG. 7c.

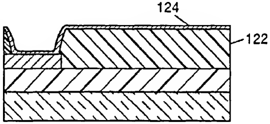


FIG. 7d.

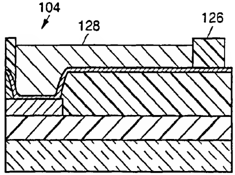
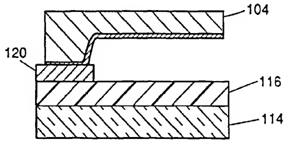


FIG. 7e.



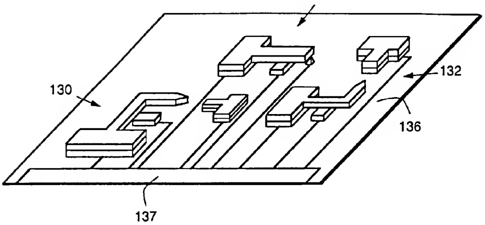


FIG. 8.

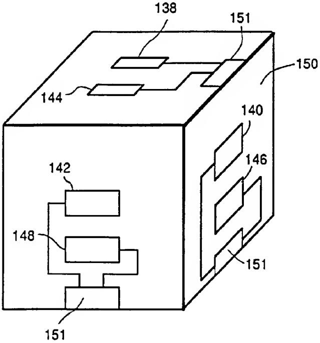


FIG. 9.